# Distribution of Ribbed Moraine in the Lac Naococane Region, Central Québec, Canada.

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**Abstract:** Ribbed moraines are large subglacially formed transverse ridges that cover extensive areas of the beds of the former Laurentide, Fennoscandian and Irish ice sheets. Since the flow speeds and stability of ice sheets are known to be sensitive to conditions operating at the bed, a full understanding of the processes of ribbed moraine genesis are critical if we are to appreciate their role in ice sheet dynamics. To date, advances in knowledge on how ribbed moraines are formed rely on inferences drawn from their characteristics. However, this approach is problematic given that ribbed moraine characteristics are poorly known. Scrutiny of the literature reveals that detailed observations are limited to small areas and rely on small sample sizes. Thus, generalisations drawn from this base cannot be regarded as being representative and remain an inadequate data source for testing the various hypotheses. The map forms part of a large study that investigated ribbed moraine characteristics in Ireland, Canada and Sweden over a combined area of 81,000 km$^2$ that has addressed this deficit. It shows the distribution of ribbed moraine ridges in the Lac Naococane region, central Québec and covers an area of 32,400 km$^2$. It comprises over 12,800 individual ridges and forms part of a database of over 33,000 individually mapped landforms which reveal ribbed moraine characteristics to be more complex than has hitherto been reported.





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# 1. Introduction

Ribbed (Rogen) moraines are large subglacially formed ridges that lie transverse to the former ice flow (Fig. 1) and cover large areas of the beds of the former northern hemisphere ice sheets. They are found commonly in the Keewatin and Québec sectors of the Laurentide Ice Sheet, on Newfoundland and in Fennoscandia. Isolated patches have also been reported in Maine, USA (Thompson and Borns, 1985), Wisconsin, USA (Attig, 1985) and on Prince of Wales Island, Arctic Canada (Dyke et al., 1992). More recently their location has been reported in Ireland (Knight and McCabe, 1997; Clark and Meehan, 2001; Dunlop, 2004; Smith et al., 2005; Dunlop and Clark, in press). A recent comprehensive literature review of ribbed moraine characteristics by Hättestrand and Kleman (1999) describe their "classic" morphology as being arcuate and concave down-ice with downstream-pointing horns and often have anatomising structures. Their size is reported to range from 300-1200 m long, 150-300 m wide and 10-30 m in height. However, more recent work by Dunlop and Clark (in press) has shown that is not the case. Using a variety of remote sensing and GIS techniques these authors mapped ribbed moraines over a combined area of 81,000 km$^2$ in Canada, Ireland and Sweden producing a database of 33,000 individual landforms. This mapping demonstrated that many published accounts of ribbed moraines are unrepresentative and confirmed that their characteristics are more complex than has been hitherto reported. In addition to displaying "classic" features, Dunlop and Clark (in press) have shown that ribbed moraine ridges can also be arcuate and concave up ice (opposite to what is usually stated), straight, rectangular, barchanoid, broad, hummocky and can be poorly formed and lack a distinct morphology. Morphometric measurements made during this study have also extended the scale range. It is now known that ridges vary between 17-1,110 m wide ($\overline{x}$ = 278 m), 1-64 m high ($\overline{x}$ = 17 m), 45-16,000 m long ($\overline{x}$ = 688 m) and have wavelengths ranging between 12-5,800 m ($\overline{x}$ = 505 m).

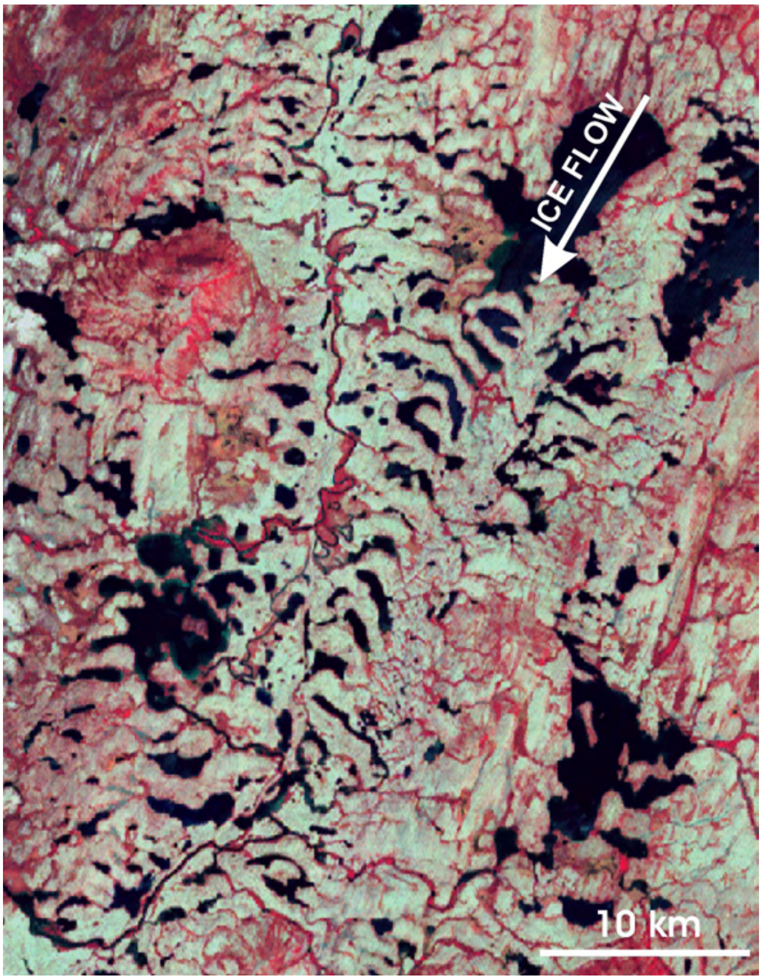


Figure 1. ASTER satellite image of a classic type ribbed moraine in the Lac Naococane region of Québec, Canada (52° 51" N & 69° 53" W).

Numerous hypotheses exist that seek to explain how ribbed moraine are formed: by shearing and stacking of subglacial sediments (e.g. Shaw, 1979; Aylsworth and Shilts, 1989; Bouchard, 1989); by deposition and reworking of sediment in subglacial cavities (Fisher and Shaw, 1992); by fracturing and extension of frozen till sheets (Hättestrand, 1997a); by sediment deformation (Boulton, 1987; Hindmarsh, 1998a, 1998b, 1999); or formation by separate stages of development (Lundqvist, 1989, 1997; Boulton, 1987; Möller, in press). Although different formational mechanisms are proposed, a common theme throughout all these papers is the reliance on data obtained from ribbed moraine characteristics (i.e. ridge morphology, sedimentology, internal structure etc) to support each hypothesis. However, scrutiny of the literature indicates that most ribbed moraine studies to date have been spatially restricted (normally $< 1{,}500$ km$^2$) and have relied on small sample sizes (i.e. usually <50 ridges) meaning published accounts of their characteristics are most likely unrepresentative. The map shows the spatial distribution of ribbed moraine ridges in the Lac Naococane region in central Québec, which is located approximately 150 to 250 km south of the main estimated Nouveau-Québec Ice Divide (Bouchard, 1989) (Fig.2). The region is liberally covered with large tracts of ribbed moraine of different scales that display a large range of morphology which made it an excellent site for studying this landform. The mapped area represents a total area of 34,225 km$^2$ of ribbed moraine terrain and forms part of the body of mapping used by Dunlop and Clark (in press) to investigate the morphological and spatial characteristics of ribbed moraines.

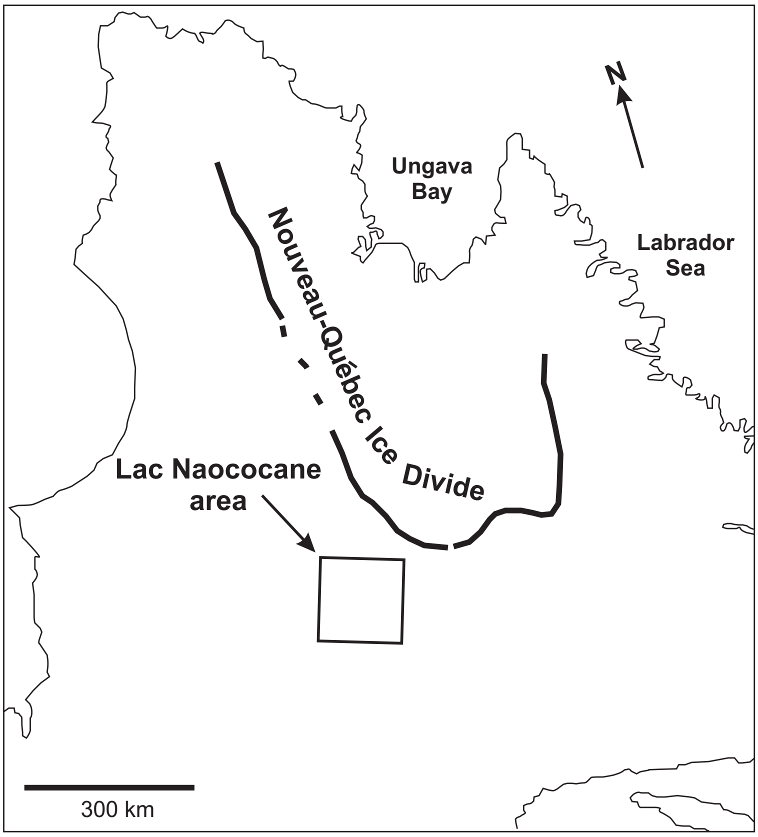


Figure 2. The position of the Nouveau-Québec Ice Divide adapted from Bouchard (1989). The Lac Naococane region is bounded by a box.

# 2. Methods

The map is based on visual interpretation of Landsat Multi-Spectral Scanner (MSS) satellite imagery of the field site, which has a spatial coverage of 185 km by 185 km and a spatial resolution of 80 m. Relatively large-scale landforms such as ribbed moraine are easily detected on this type of imagery, although it is not possible to resolve smaller forms such as minor ribbed moraine. Therefore, high resolution ASTER images (15 m in the Visible and Near Infrared bands) were used to assess the accuracy of the map and to identify ridges too small to be detected on MSS imagery. Prior to mapping, all images were georeferenced to UTM 19 North, thus, the interpreted geomorphology map contains the same projection parameters. Mapping was achieved by visual interpretation of the landforms and by on-screen digitising the ridge crests directly into a Geographic Information System (GIS) (Fig. 3). All the data were stored digitally as ARC/INFO coverages. Ribbed moraine are conspicuous landforms consisting of large intact ridges, smaller broken ridges and loosely joined hummocks and where possible, all these features were mapped. During mapping, no distinction was made between the various morphological types of ribbed moraine reported in the literature, for example, Rogen moraine (Lundqvist, 1969), Blattnick moraine (Markgren and Lassilla, 1980), minor ribbed moraine (Hättestrand, 1997a) and all were treated as one generic type of morphology, i.e. ridges composed of drift that were formed transverse to the known ice flow direction. This was due the findings of Hättestrand (1997), who after investigating the spatial distribution of these different classes of ribbed moraine in Sweden, concluded their shared spatial characteristics were indicative of a common subglacial origin. The final map comprises of 12,851 individual ridge crests and differs significantly from other traditional glacial geomorphology maps (e.g. Prest et al., 1968; Hättestrand, 1997b; Jansson, 2005) in that it shows the actual distribution of the ridge crests rather than simply the outline of ribbed moraine fields. This has the advantage of allowing more detailed spatial analysis of the landform and, because the data is in digital format, it is easily manipulated in a GIS. Additional context has been added to the map as a backdrop. Three of the largest lakes in the region have been included as points of reference and the ridges have been draped over a relief image derived from a GTOPO30 DEM (30-arc second resolution or approximately 0.5 - 1 km; http://edcdaac.usgs.gov/gtopo30/gtopo30.asp) to show the regional topography.

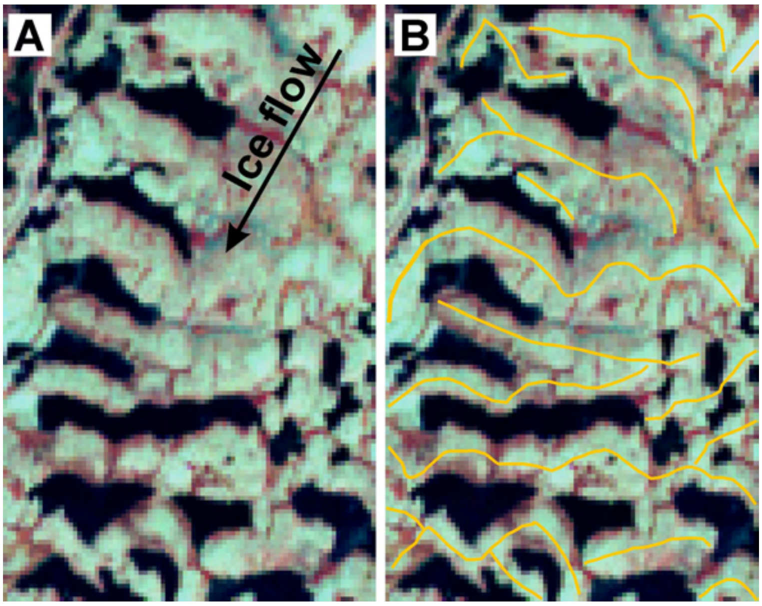


Figure 3. Demonstration of the method employed to map ribbed moraine ridge crests. (A) ASTER image of a ribbed moraine field in the Lac Naococane region (52° 43" N & 69° 59" W). (B) Shows an example of some digitised ridge crests. Note the images are not a stereo pair.

# 3. Map Analysis

Mapping ribbed moraines using this approach has yielded valuable new information on this landform. The map clearly shows that ribbed moraine fields are formed at a wide range of scales and can vary anywhere between a few square kilometres, to extremely large expanses of continuous ribbed moraine measuring several thousand square kilometres in extent. For example, the largest unbroken ribbed moraine field observed in the Lac Naococane region measures approximately 2,300 km$^2$. Previous reports of field size measured in Québec state they range from only 2 to 30 km$^2$ (Bouchard, 1989). Bouchard (1989) recognised that they did cover larger areas but did not give estimates of the size range. In Sweden, the largest field in the Glacial Geomorphology Map of Central and Northern Sweden (Hättestrand, 1997b) measures approximately 1,000 km$^2$. We thus find the ribbed moraine fields (i.e. continuous tracts of ribbed moraine) are far more extensive than hitherto reported. Visual analysis of this map (Dunlop and Clark, in press) found that in general the distribution pattern of ribbed moraine fields at a regional scale could be classified as follows:

1. Extensive continuous fields of large size
2. Elongate ribbons and narrow tracks
3. Densely packed or dispersed clusters of ribbed moraine
4. Isolated fields

Morphometric data was also obtained from the digitised landform's attribute table. Figure 4 shows the distribution of ridge lengths measured in the Lac Naococane region. At this site, ridge length ranges from 180 m to 5,900 m, with a mean ridge length of 918 m. Dunlop and Clark, (in press) combined these data with data from similar maps of ribbed moraine and found that the scale range of ridge length extended significantly from 300-1,200 m long reported by Hättestrand and Kleman (1999) to 45-16,000 m long.

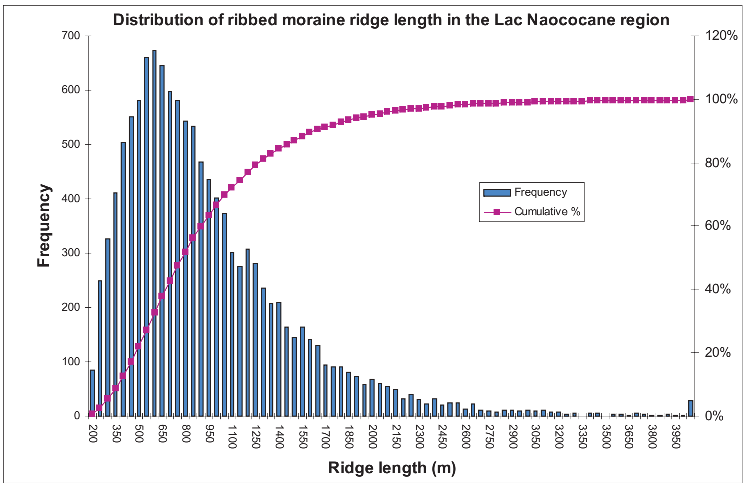


Figure 4. Distribution of ribbed moraine ridge length from a sample of over 12,000 mapped ridges in the Lac Naococane region. 90% of the ribbed moraine ridges range in length from 200 m to 2,000 m, with the mode at 600 m.

Ribbed moraine occurrence has commonly been associated with topographic depressions or slopes that face upstream (Lundqvist, 1969, 1989; Sugden and John, 1976; Shaw, 1979; Markgren and Lassilla, 1980; Mollard and James, 1984; Bouchard, 1989; Sollid and Sørbel, 1994; Menzies and Shilts, 1996). To assess this observation, the map was superimposed onto a regional-scale GTOPO30 DEM (Fig. 5). This demonstrates that ribbed moraines are located in a wide variety of topographic settings including basins and topographic depressions (as widely reported), and also on slopes running in and out of major basins, on hilltops, and hill slopes in all directions relative to ice flow (Fig. 5). Whilst a long-standing association of ribbed moraine and depressions has been widely reported, this evidence, and that of other researchers (Aylsworth and Shilts, 1989; Hättestrand and Kleman, 1999; Clark and Meehan, 2001) demonstrates that ribbed moraines are not confined to basins and form independent of topography.

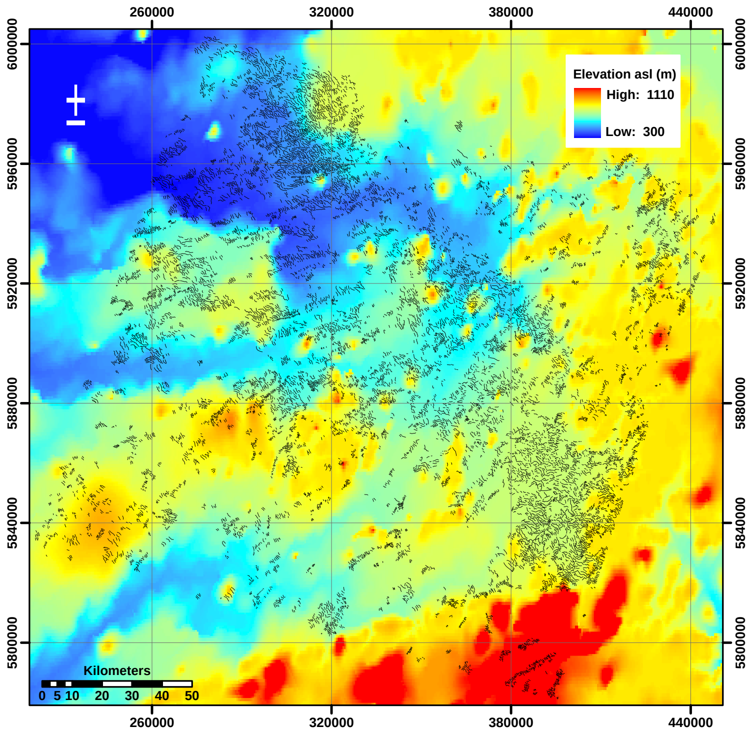


Figure 5. A colour coded GTOPO30 DEM of the Lac Naococane region with the ribbed moraine crests superimposed on top. Elevation is coded to show the highest elevations as red, grading down to orange, yellow, green, light blue to dark blue, which represents the lowest lying regions. Note how the ribbed moraines are not topographically confined in this locality and are situated in a wide variety of topographic situations. Note that many of the ridges appear to be merged as a result of the map being reduced in size. Please compare data with the accompanying map.

# 4. Conclusions

The geomorphological map of ribbed moraine ridges presented here is the first detailed map of its kind and the approach of mapping individual ridge crests has yielded valuable new information on the characteristics of this landform. The map demonstrates that ribbed moraine fields form at a much wider variety of scales than has been previously reported. It also shows that ribbed moraine fields at a regional scale display a range of morphologies. Morphometric data extracted from the map has extended the scale range of this landform and we now know that they form independent of topography. The map forms part of a much larger representative database of ribbed moraine characteristics that has been compiled from similar maps of different ribbed moraine areas (Dunlop and Clark, in press). Such data is important as it should enable formal falsification of various theories and may be used to generate new hypotheses of ribbed moraine formation.

# Software

All image processing and mapping was carried out using ERDAS Imagine 8.7. The geomorphological map was produced using ArcGIS version 9.1.

# Data

The author has supplied data (as an ESRI Shapefile) used in the production of the accompanying map. This PDF has a ZIP archive embedded within it (stored as a .ZI file extension) containing the data and can be accessed by right-clicking on the "paperclip" icon at the beginning of this section (you will need to save the file and edit the file extension to .ZIP). Whilst the contents of the ZIP file are the sole responsiblity of the author, the journal has screened them for appropriateness.

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